AMERICAN JOURNAL OF PHYSICAL ANTHROPOLOGY 112:191–205 (2000)

Regional Variations in Cortical Modeling in the Femoral Mid-Shaft: Sex and Age Differences

S.A. FEIK,* C.D.L. THOMAS, R. BRUNS, AND J.G. CLEMENT
School of Dental Science, University of Melbourne, Victoria 3000, Australia

ABSTRACT Modern lifestyle changes may result in site-specific alterations in the skeleton. Our aim was to determine sex and age differences in regional geometry at the mid-femur. Complete cross sections from 113 individuals aged 20–97 years from a modern Australian population were obtained. A further subsample of 24, in whom the precise orientation of specimens was known, was subsequently collected. Microradiographs were made of 100-μm sections and the bone was analyzed using image processing software (Optimas, Media Cybernetics). The periosteal boundary was extracted automatically and the centroid of the periosteal outline was calculated. Fourier shape analysis was used to delineate the endocortical surface. Radial and cortical widths in each quadrant were determined. The posterior was identified by the linea aspera, and the medial and lateral were indistinguishable and therefore grouped together. For analysis, the entire sample was divided into three groups: young (20–40 years), middle (41–60 years), and old (61+ years). Raw and height-normalized values were analyzed with SPSS using *t*-tests, analysis of variance, and Tukey's honestly significant difference (HSD) tests. The results show that with age the femoral mid-shaft in both sexes becomes larger and more circular, with a slight shift towards the anterior. Apposition is least on the posterior and resorption greatest on the anterior, the latter being particularly evident in postmenopausal females. The greatest sex differences are seen in the middle years, lessening again in the old. We conclude that differential circumferential modeling in response to functional and postural changes occurs in both sexes with age. Am J Phys Anthropol 112: 191–205, 2000. © 2000 Wiley-Liss, Inc.

It is well-known that the skeleton is highly reactive in life and that some of the changes that can be observed postmortem are, in part, attributable to lifestyle and environmental factors. For people living in prosperous, highly urbanized societies (such as Australia) during the last 100 years, there have been dramatic improvements in living conditions. In particular, there has been a considerable decrease in the need to engage in vigorous physical activity. This decrease has been the result of changes in methods of transport, the reduction in hard physical labor needed to earn a living, and other lifestyle changes.

The increasing prevalence of lifestyle-linked diseases like osteoporosis makes it clear that humans need to engage in at least a minimum of physical activity. Osteoporotic fracture incidence is increasing and is predicted to increase still further (Boereboom et al., 1992; Melton, 1993). The decline with age in bone mineral density (BMD), as measured by dual-energy X-ray absorptiometry (DEXA), explains merely a doubling of

*Correspondence to: Sophie A. Feik, School of Dental Science, University of Melbourne, 711 Elizabeth St., Melbourne, Victoria 3000, Australia. E-mail: s.feik@dent.unimelb.edu.au

Received 4 August 1999; accepted 24 January 2000.

the risk of hip fracture between 60–80 years, whereas the actual risk increases 13-fold (De Laet et al., 1997).

The trend is to move away from studying global changes, towards examining more localized, i.e., site-specific changes that may better predict fracture risk (Beck et al., 1992, 1993, 1996). This argument is strengthened by findings such as those of Adami et al. (1999), showing that exercise regimens, even site-specific directed ones, may have little effect on BMD but may reshape the bone segment under stress by increasing both the cross-sectional area and the density of the cortical component. This has important consequences for the anthropological study of contemporary human populations. Animal studies have confirmed that adaptation to altered loading regimes may occur through changes in bone geometry rather than bone mass via regulation of local strain (Judex et al., 1997; Mosley et al., 1997; Woo et al., 1981). Modern techniques such as peripheral quantitative computed tomography and magnetic resonance imaging are increasingly being used in attempts to determine geometric changes in vivo. The advent of automated image analysis techniques has enabled detailed studies of site-specific modeling and remodeling from bone obtained after death or at surgery. Bell et al. (1999) recently used such an image analysis technique to study the structure of the femoral neck in hip fracture cases and controls. They found that bone loss was not uniform throughout the cortex, there being a proportionately greater bone loss in particular regions of the neck in the fracture cases. The numbers in this study were small, and only females within a limited age range were examined. A detailed study of sex and age differences in bone distribution within the cortex of the femur needs to be conducted to gain a better understanding of the process, both for anthropological reasons and to devise preventive and treatment strategies to reduce fracture risk. The mid-shaft of the femoral diaphysis has been chosen, for many earlier studies on cross-sectional bone geometry have been conducted on bone from this site (Martin et al., 1980; Ruff and Hayes, 1982, 1988; Smith and Walker, 1964), thereby providing a basis for comparison.

Ruff and Hayes (1983b), in a study of an archaeological population, showed that in the femoral diaphysis the geometry of the bone was such that males had a relatively greater bending rigidity in the anteroposterior plane and females in the mediolateral plane. They attributed these differences to sexual dimorphism in pelvic structure and to probable behavioral differences between males and females in this particular population. They stated that it would be interesting to see if these same differences are characteristic of modern populations. They also studied age changes in site-specific modeling, concluding that these changes appeared to selectively conserve more cortical bone in areas of high mechanical stress. However, by their own admission (Ruff and Hayes, 1983a), a study of an archaeological collection, rather than a modern autopsy collection, has the disadvantages of having to estimate sex and age. Their oldest category was 50+ years, and age determination based on anatomical changes, such as endocranial suture closure in adults over 40 years, is imprecise.

A further spur to this investigation was the finding by Ferretti et al. (1998) that women during the reproductive period, i.e., until menopause, stored more mineral than age-matched men with comparable lean body mass. The authors speculated whether this "surplus" bone per unit muscle mass in women during this life phase accumulated in mechanically optimal or less optimal regions of the skeleton. They could not answer this question because of the nature of their study, using DEXA to determine total bone mineral content (TBMC). Examining site-specific modeling/remodeling changes with age in both sexes could provide an answer to this question.

In previous studies on a large, modern, well-characterized sample, sex and age differences in femoral mid-shaft geometry (Feik et al., 1996) and porosity (Feik et al., 1997) were investigated, using automated image analysis to examine global changes in entire cross sections. In this paper, using material from the same sample, we report on regional changes in bone geometry

around the cortex at the same mid-shaft site. Mathematical and image processing methods have been developed and used to enhance reproducibility. To our knowledge, this is the first time Fourier shape analysis has been used to assist in delineating the endocortical surface. Comparison of the results from this study with previously reported findings from archaeological populations may shed some light on the changes wrought in the skeleton by modern urban living.

MATERIALS AND METHODS

Bone specimens (n = 113) were collected at the Victorian Institute of Forensic Medicine, Melbourne, Australia, between 1990–1993 from people who had died suddenly with no known diseases directly affecting their bones. The sample was almost exclusively Anglo-Celtic, as judged by names. Information was available on the age, sex, supine length and weight, and in almost every case, the cause of death of the subjects. Supine lengths were measured by mortuary staff using a rigid ruler; this procedure may have overestimated the lengths of cadavers by up to 5 cm. Collection of specimens from both sexes representing each year from 20–100 years of age was attempted. Specimens 2–4 cm in length were sawed from the mid-shaft of either femur by mortuary staff. Unfortunately, the technicians were not asked to record or mark the medial and lateral aspects of the specimens, and this information was lost. A further subsample of 24 specimens of both sexes (20–40 years, n = 11; 61+ years, n = 13) was collected by one of the authors (R.B.) during 1998. Additional information beyond that available for the larger sample was obtained. All these femora were taken from the right side, and the femoral lengths were measured before the proximal two thirds of the bones were dissected out. Prior to removal of mid-shaft specimens from these bones, the medial, lateral, posterior, and anterior surfaces were marked. All the specimens, details of which are presented in the first two columns of Table 2, were fixed in 70% ethanol.

Microradiography and image acquisition

Transverse sections, approximately 300 μm thick, were cut from the femoral blocks using a Leitz 1600 sawing microtome (Leitz, Wetzlar, Germany), and planoparallel sections with a nominal thickness of 100 μm were obtained from these by hand lapping on 1200-grade wet and dry carborundum paper, using a custom-made tool. The sections were microradiographed using a Matchlett Laboratories OEG X-ray tube with a copper target operated at 25 kV and 10 mA. The film used was Kodak SO-343 at a distance of 195 mm from the target. The microradiographs were mounted on glass slides and masked with black tape to define the borders and to control scattered light. Each entire cross section was recorded as an array of monochrome transmitted light images, using a computer-controlled X-Y stage (Lang Electronics MCC12-JS-RS 232) fitted to a Leitz Dialux 20 microscope. The camera used was a three-chip color video camera (Sony DXC-930P), and the video digitizer a Targa+ board (Truevision Inc, Indianapolis, IN) working at a resolution of 512 × 576 pixels. The image processing software used was Optimas (Media Cybernetics), and data were recorded using Microsoft Excel. The field of view of the camera, using a ×1 microscope objective (Leitz PL 1/0.04 and matching condenser), was ~3.5 × 2.5 mm, and most sections were contained within a rectangle 30 × 35 mm, so that approximately 120 frames were needed to cover each specimen. Frame boundaries matched to a precision of 1 μm. In addition to the images of the bone, a brightfield image was acquired with a neutral density filter on the microscope stage. Each image of bone acquired was corrected for variations in illumination by dividing it by the brightfield image and multiplying by the average brightness of the brightfield image.

Montage reconstruction and data collection

The images making up a single cross section were combined into a montage (Fig. 1), using software written in the Optimas macro language. In these images the background and voids that penetrated the bone section appeared black. All lighter tones represented bone, variations in brightness being due to either the degree of mineralization of the bone or to slight differences in

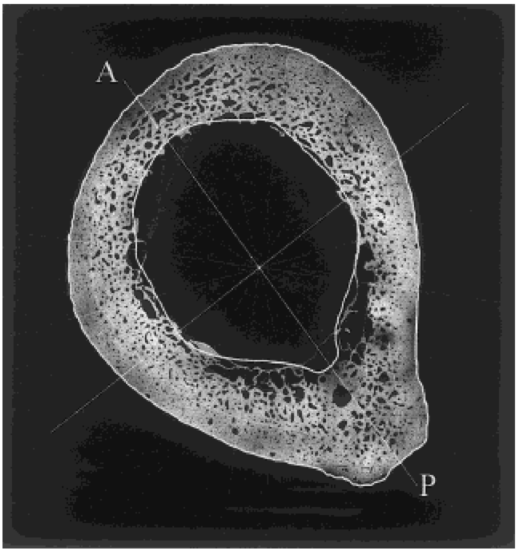

Fig. 1. A typical mid-femoral bone cross-section. Overlaid in white are the periosteal and endocortical outlines, as determined by methods described in the text. The straight lines show the A-P and M-L axes used.

thickness of the section. A threshold brightness level of 50 (in a range of 0–255, where 0 is black) was chosen empirically to distinguish bone from background in the images. Based on this threshold, the outlines of the periosteal and endocortical boundaries of the bone were extracted automatically, using features provided by the Optimas image processing package. Having isolated the periosteal outline, Optimas calculated the location of its centroid, and this value was recorded. In previous research the definition of the endocortical surface has been a problem in cases where it is not smooth and clearly defined. Some workers have estimated the location of the line marking the division between areas with less than 50% porosity and those more porous (Ruff and Hayes, 1984). In previous work, the current authors drew in the endocortical surface, attempting to separate trabecular from cortical bone by eye (Feik et al., 1996), but they felt that this process was too subjective to be reproducible. In order to provide an objective, consistent definition of the endocortical surface, the raw surface outline as found above was decomposed into a series of Fourier shape descriptors (e.g., see Schwarcz and Shane, 1969; Luerkens et al., 1982; Lestrel, 1997), again using a facility provided within Optimas. The outline was then reconstructed from a version of the Fourier series truncated at the eighth harmonic. The effect of this is to remove features smaller in scale than one eighth of the outline. On rare occasions, manual editing of the outlines was necessary to remove gross features from the surface prior to the Fourier smoothing.

Following the automatic location of the outlines of the bone surfaces, they were displayed on the computer screen as overlays on the image (Fig. 1). The operator then marked a point in the center of the linea aspera, and a line joining this point to the opposite periosteal surface, passing through the centroid of the periosteal outline, was used to define the anteroposterior (A-P) axis. Seven more diametral lines were then automatically constructed at equal increments of angle so as to divide the bone cross section into 16 sectors. The line perpendicular to the A-P line defined the mediolateral (M-L) direction. The other constructed lines were used to divide the cortex for a study of porosity distribution, the results from which will be reported subsequently. The distances along the A-P and M-L lines from the centroid to the endocortical and periosteal surfaces were measured by the operator, who marked the points where the lines intersected the surface outlines. Calibration of the distance measurements was achieved by measurement of the size of the field of view recorded in each individual image. This measurement was achieved using a stage micrometer (no.310345; Wild, Heerbrugg, Switzerland).

The distance to the periosteal surface will be referred to as the “radial width” (RW) of the bone, and the difference between this distance and the endocortical radius will be referred to as the “cortical width” (CW). There are ambiguities in our definition of radial width because the centroid of the periosteal outline will move as the periosteal outline changes. However, changes in the diameter of the bone can be measured unambiguously, and thus changes in the sum of the reported radii will be correct. The apportioning of any such change to one or another radial direction is subject to interpretation. If there is apposition on the ante-

rior surface, then the centroid will move forward relative to the posterior surface. This forward movement will reduce the amount of change measured in the anterior radial width. It cannot, however, turn an increase into a decrease, and thus the reported changes are clear underestimates of actual movements.

A measure of the "shape" of the shaft (first described and quantified by Busk in 1863) was calculated as the ratio of M-L shaft diameter to A-P shaft diameter; when taken at the level of the midpoint of the maximum length of the bone, it is referred to as the mid-shaft index (Lovejoy et al., 1976). All measurements were transferred via a dynamic data exchange (DDE) link to a Microsoft Excel spreadsheet, DDE being useful for eliminating transcription errors.

Data analysis

Size normalization. Ruff (1984) and Ruff et al. (1993) have demonstrated that femoral cross-sectional size varies with bone length. As it is known that the length of the femur is approximately one quarter of the height of an individual (Feldesman and Fountain, 1996), the differences in height between individuals may thus affect the measured parameters independently of aging or other variables. In the subsample of 24 individuals described above, the relationship between height and femoral length was confirmed, with height being predicted by the regression equation:

$$\text{Height (cm)} = 69.5 \text{ cm} + 2.26 \times \text{femoral length (cm)} \quad (r^2 = 0.44).$$

In this sample, the femur formed an average of 0.26 of the height with a standard deviation of 0.01 and a range from 0.22–0.29. In view of these relationships, results are presented as both raw measured values and in a height-normalized version. In the case of height-normalized values, the results are presented in units of millimeters of measured width per millimeter of height, multiplied by 100 to remove leading zeros after the decimal point.

Medial vs. lateral comparisons. As described above, it was not possible to distinguish between medial and lateral in the majority of the specimens collected, whereas the posterior surface could be identified by the presence of the linea aspera. The subsample of 24 for which the anatomical orientation was known made it possible to test for the impact of this ignorance on the analysis of the results. *T*-tests (SPSS V8.0) were used to compare the means of the radial and cortical widths on the medial and lateral sides. The results are summarized in Table 1, and this shows that differences between the sides did not approach statistical significance for either measurement. In view of this result, the authors decided to combine medial with lateral in all cases and treat the bones as having three distinct aspects: medio-lateral, posterior, and anterior.

TABLE 1. Comparisons between medial and lateral widths[1]

	RW	CW
Medial	12.99 ± 1.31	6.90 ± 1.01
Lateral	13.16 ± 1.31	7.00 ± 1.17
Difference	−0.172	−0.099
P value	0.65	0.76

[1] RW, radial width (mm); CW, cortical width (mm). All values are mean ± 1 SD.

Statistical analysis of results. All analysis was done using version 8.0 of the Statistical Package for the Social Sciences (SPSS). For analysis, the sample was grouped by sex and age: young (20–40 years), middle (41–60 years), and old (61 years and older). The age groups were chosen such that the youngest person should have completed growth, the middle-aged group should cover women going through menopause and its aftermath, and all females in the oldest group should be truly postmenopausal. For males, the mean ages of the groups were 28 (SD 6.2), 53 (SD 6.1), and 77 (SD 8.7) years; and for females, 29 (SD 6.7), 49 (SD 6.3), and 76 (SD 8.4) years. The values of all measured parameters were found to be normally distributed, and comparisons between pairs (e.g., males vs. females) of means used independent-samples *t*-tests. Where more than two comparisons were being made (e.g., between all the three age groups), a single-factor analysis of variance (ANOVA) was used, followed by a Tukey's honestly significant difference (HSD) test.

RESULTS

Heights and femoral lengths

The mean supine lengths of the three groups (young, middle, and old) were, in males, 178.68 (SD 6.04), 171.47 (SD 6.5), and 168.38 (SD 7.9) cm, respectively; in females, the equivalent supine lengths were 166.61 (SD 7.19), 162.41 (SD 6.39), and 155.18 (SD 8.37) cm. Hamill et al. (1977) suggested that approximately 1 cm provides a reasonable adjustment for adolescents and adults between supine length and standing height. In both sexes there was a statistically significant ($P < 0.05$) difference between young and old groups, indicating a decline in height with age, whether as a result of secular change and/or statural loss with increasing years. Between young and old groups there was a 5.8% (10.31 cm) and a 6.9% (11.43 cm) decrease in males and females, respectively. In the subsample the mean femoral length in males was 44.53 cm with a femoral length/supine length ratio of 0.259; the corresponding figures for females were 42.09 cm and 0.262. The differences between the sexes were not statistically significant, and the femur/stature ratio showed no correlation with age ($R^2 = 0.001$).

Age differences in femoral geometry

Males: raw values (Table 2, Fig. 2Ai). Between the young and old there is a significant increase of ~11% in the medio-lateral (M-L) diameter. The greatest difference ($P < 0.05$) is observed between the young and middle groups, with a smaller increase thereafter. By contrast, the antero-posterior (A-P) diameter shows no significant differences between the age groups, being actually larger in the young, although not significantly so. These changes result in a significant increase in the mid-shaft index between the young and middle groups, which is further accentuated with age. Trends in the radial widths (RW) of the posterior and anterior quadrants differ, with the anterior showing a tendency to increase with age and the posterior to decrease, although none of the group differences are significant. The cortical widths (CW) in all quadrants similarly show no significant group differences, despite a tendency to decline in the elderly. The relative

TABLE 2. Raw values of parameters studied[1]

Age (years)	N	RW (M-L)	CW (M-L)	RW (Post.)	RW (Ant.)	CW (Post.)	CW (Ant.)	CW/RW (M-L)	CW/RW (Post.)	CW/RW (Ant.)	Mid-shaft index[2]
Male											
20–40	19	12.88 ± 1.11	7.11 ± 1.38	15.93 ± 1.68	14.42 ± 1.11	9.74 ± 1.99	6.10 ± 1.32	0.55 ± 0.08	0.61 ± 0.10	0.43 ± 0.10	0.86 ± 0.12
41–60	16	13.99 ± 1.27*	7.79 ± 1.25	15.55 ± 1.18	14.62 ± 1.31	9.02 ± 1.89	6.11 ± 1.56	0.56 ± 0.09	0.58 ± 0.10	0.42 ± 0.11	0.94 ± 0.10*
61+	37	14.27 ± 0.82*	7.12 ± 1.32	15.40 ± 1.21	14.83 ± 1.14	8.68 ± 1.90	5.45 ± 1.31	0.50 ± 0.09	0.56 ± 0.12	0.37 ± 0.09	0.95 ± 0.08*
Female											
20–40	19	12.30 ± 0.92	6.88 ± 0.67	14.48 ± 1.47	13.05 ± 0.87	8.80 ± 1.85	5.26 ± 0.63	0.56 ± 0.06	0.61 ± 0.09	0.40 ± 0.04	0.90 ± 0.09
41–60	17	12.15 ± 0.74	6.79 ± 1.12**	13.69 ± 1.50	12.53 ± 1.19	8.05 ± 1.85	4.83 ± 0.91**	0.56 ± 0.08**	0.59 ± 0.10	0.39 ± 0.08*	0.93 ± 0.09
61+	29	12.67 ± 1.00	5.97 ± 0.69*	13.83 ± 1.50	13.09 ± 0.97	7.25 ± 1.76*	4.17 ± 0.98*	0.47 ± 0.06*	0.52 ± 0.09*	0.32 ± 0.08*	0.95 ± 0.11

[1] M-L, medio-lateral; Post., posterior; Ant., anterior; RW, radial width (mm); CW, cortical width (mm). All values are mean ± 1SD.
[2] Calculated as: medio-lateral diameter/antero-posterior diameter.
* Significant ($P < 0.05$) differences between these values and those for the 20–40 year group.
** Significant ($P < 0.05$) differences between these values and those for the 61+ year group.

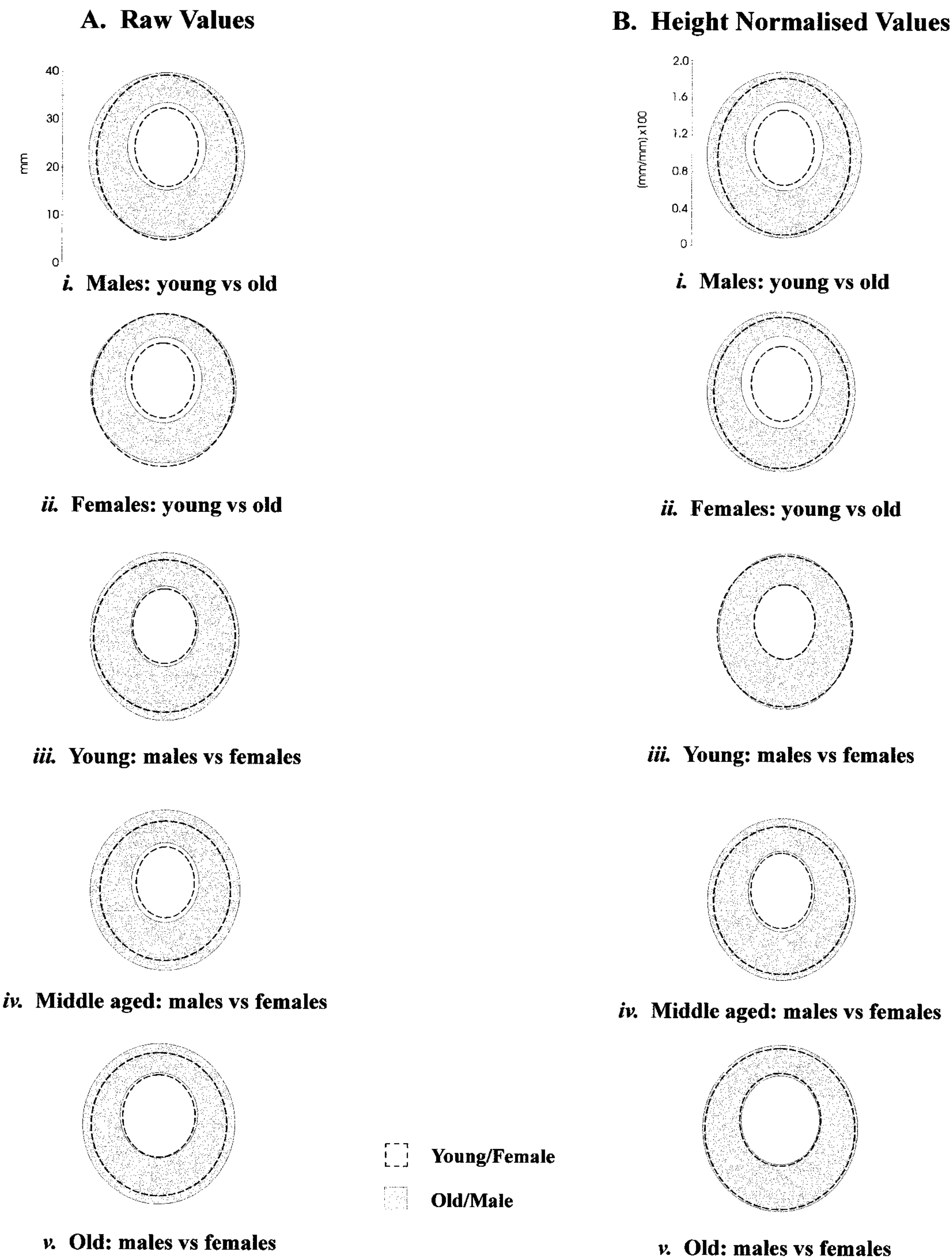

Fig. 2. **A:** Raw values. **B:** Height-normalized values. Diagrammatic comparisons of male vs. female and young vs. old mid-femoral bone cross-sections. A-P and M-L radial and cortical widths are drawn to scale; bone outlines are approximated by ellipses.

cortical widths (CW/RW) show a tendency to decline in the elderly in all quadrants, but none of the differences are significant.

Males: height-normalized values (Tables 3 and 4, Fig. 2Bi). Height-normalized values are presented in greater detail

TABLE 3. Height-normalized values of parameters studied[1]

Age (years)	RW (M-L)	CW (M-L)	RW (Post.)	RW (Ant.)	CW (Post.)	CW (Ant.)
Male						
20–40	0.72 ± 0.07	0.40 ± 0.08	0.89 ± 0.09	0.81 ± 0.07	0.55 ± 0.11	0.34 ± 0.07
41–60	0.82 ± 0.06*	0.45 ± 0.08	0.91 ± 0.08	0.85 ± 0.06	0.53 ± 0.13	0.35 ± 0.09
61+	0.85 ± 0.05	0.42 ± 0.08	0.92 ± 0.07	0.88 ± 0.06*	0.52 ± 0.11	0.32 ± 0.08
Female						
20–40	0.74 ± 0.06	0.41 ± 0.05	0.86 ± 0.08	0.78 ± 0.05	0.52 ± 0.11	0.31 ± 0.03
41–60	0.75 ± 0.04**	0.42 ± 0.07	0.84 ± 0.09	0.77 ± 0.06**	0.50 ± 0.11	0.30 ± 0.06
61+	0.82 ± 0.08*	0.38 ± 0.05	0.90 ± 0.09	0.85 ± 0.05*	0.47 ± 0.11	0.27 ± 0.06*

[1] M-L, medio-lateral; Post., posterior, Ant., anterior; RW, radial width ((mm/mm) × 100); CW, cortical width ((mm/mm) × 100). All values are mean ± 1 SD.
* Significant ($P < 0.05$) differences between these values and those for the 20–40 year group.
** Significant ($P < 0.05$) differences between these values and those for the 61+ year group.

TABLE 4. Age differences in height-normalized values of parameters studied[1]

Percentage change: 20–40 years (young) to 61+ years (old)[2]	Male	Female
M-L diameter	17.6*	10.5*
RW (medio-lateral)	17.5*	10.3*
CW (medio-lateral)	6.3	−7.4
A-P diameter	5.7*	5.9*
RW-posterior	2.7	3.2
RW-anterior	9.0*	7.7*
CW-posterior	−5.6	−9.9
CW-anterior	−5.4	−14.9*
CW/RW (medio-lateral)	−9.3	−16.0*
CW/RW (posterior)	−7.6	−13.9*
CW/RW (anterior)	−13.0	−19.0*
Mid-shaft index[3]	10.7*	5.5

[1] M-L, medio-lateral; A-P, antero-posterior; RW, radial width; CW, cortical width.
[2] [(old-young)/young] × 100.
[3] Calculated as: medio-lateral diameter/antero-posterior diameter.
* $P < 0.05$.

as the effects of secular changes in stature are minimized, thereby enhancing the possibility of detecting patterns of change with age in individuals. The M-L diameter shows an even greater increase between the young and the old than described above (~18% vs. ~11%). Again the greatest difference is seen between the young and middle groups, with an ~12.5% increase ($P<0.05$) in RW between these groups, and a smaller (~5%) nonsignificant change between the middle and old groups. The A-P diameter, in contrast to that described above, does show a small (~6%) but significant increase between young and old. As above, RW changes in the anterior quadrant are greater than in the posterior. There is a significant increase (~9%) in the anterior RW between young and old, while the differences between these groups in the posterior RW (~3% increase) are not significant. CWs, as above, show no statistically significant differences between any of the groups. However, there is a tendency for all the CW dimensions, except the posterior, to increase between the young and middle groups, and for all the CWs to then decline in the elderly. So it appears that in males after skeletal maturity is attained, periosteal apposition continues, albeit more slowly in the elderly. However, this is not uniform around the shaft circumference; more bone is deposited on the medial and lateral periosteal surfaces, less on the anterior, and least on the posterior, so that the shape of the mid-femoral shaft is altered, becoming rounder with age. Thus the differential modeling favors greater M-L bending rigidity and anterior loading with age. Endocortical resorption appears to exceed periosteal apposition in the old; however, because of the earlier gains in RW, the loss is insufficient to significantly alter the CWs. The posterior shaft shows the least apposition and a small steady decline in width with age.

Females: raw values (Table 2, Fig. 2Aii). There are no significant differences between any of the groups, young, middle, or old, in M-L or A-P diameters. However, between young and old, the M-L diameters show a tendency to increase and the A-P to decrease, with the greatest changes evident between the middle and old groups. The mid-shaft index does not change significantly with age. The RWs, similarly, show no significant differences, and comparable trends, between young and old groups. The tendency to a decline in A-P dimensions is largely due to a decrease in posterior RW,

TABLE 5. Differences (male minus female) between sexes in mean values of parameters studied[1]

	Raw values					
	20–40 years		41–60 years		61+ years	
	Difference	*P* value	Difference	*P* value	Difference	*P* value
M-L diameter (mm)	1.2	NS	3.7	0.000	3.2	0.000
RW (M-L) (mm)	0.579	NS	1.836	0.000	1.6	0.000
CW (M-L) (mm)	0.229	NS	0.994	0.022	1.158	0.000
A-P diameter (mm)	2.8	0.001	3.8	0.000	3.3	0.000
RW-Post. (mm)	1.451	0.007	1.861	0.000	1.576	0.000
RW-Ant. (mm)	1.376	0.000	1.94	0.000	1.735	0.000
CW-Post. (mm)	0.944	NS	0.974	NS	1.431	0.003
CW-Ant. (mm)	0.84	0.017	1.176	0.011	1.276	0.000
Mid-shaft Index[2]	−0.041	NS	0.003	NS	0.001	NS

	Height-normalized values					
	20–40 years		41–60 years		61+ years	
	Difference (mm/mm) × 100	*P* value	Difference (mm/mm) × 100	*P* value	Difference (mm/mm) × 100	*P* value
M-L diameter	−0.042	NS	0.132	0.002	0.057	NS
RW (M-L)	−0.021	NS	0.066	0.002	0.028	NS
CW (M-L)	−0.014	NS	0.034	NS	0.041	0.02
A-P diameter	0.048	NS	0.154	0.002	0.055	NS
RW-Post.	0.027	NS	0.07	0.024	−0.02	NS
RW-Ant.	0.099	NS	0.083	0.001	0.036	0.016
CW-Post.	0.024	NS	0.035	NS	0.046	NS
CW-Ant.	0.029	NS	0.055	0.048	0.057	0.002

[1] M-L, medio-lateral; A-P, antero-posterior; Post., posterior; Ant., anterior; RW, radial width; CW, cortical width. NS, not significant at $P > 0.05$.
[2] Calculated as: medio-lateral diameter/antero-posterior diameter.

with a slight increase in the anterior. In all quadrants the CWs are significantly smaller in the old as compared to the young: M-L ~13%, posterior ~18%, and anterior ~21%. Significant differences are also detected between the middle and old groups in the M-L and anterior quadrants but not in the posterior. The CW/RW ratios in all quadrants also decline significantly with age, showing a similar pattern to that displayed by the CWs.

Females: height-normalized values (Tables 3 and 4, Fig. 2Bii). In contrast to the results seen above, when values are height-normalized, the M-L (~10%) and A-P (~6%) diameters increase significantly from young to old. The greatest changes are again evident between the middle and old groups, with relative stability between the young and middle groups. The RW changes reflect those seen in the diameters. However, in the A-P plane, as seen with the raw values, the greatest change occurs in the anterior quadrant, with no significant alterations in the posterior. Although the CWs show a tendency to decline in all quadrants, only in the anterior is the decrease between young and old significant.

So, in females, there is very little change in any of the dimensions until after the menopausal period; then, modeling increases. Periosteal apposition is slightly greater medio-laterally than antero-posteriorly and, in the latter instance, more bone is deposited on the anterior surface and less on the posterior. The older bones are therefore larger and somewhat rounder, with a slight shift towards the anterior. In the elderly, medullary resorption exceeds periosteal apposition around the entire endocortical perimeter; however, the loss is not uniform: endocortical resorption is greatest anteriorly, so the cortex is narrowest here (both absolutely and relatively) and widest posteriorly, where the loss is not as great.

Sex differences in femoral geometry (Table 5)

The raw data {Table 2, Fig. 2Aiii, iv, v) show that mean values for males are consistently greater than those for females, except in the case of the mid-shaft index. In the young this index is greater in females, although not significantly so, and in the old the indices are identical. The differences observed between the sexes in the other pa-

rameters are all highly significant with a few notable exceptions, e.g., all the M-L dimensions in the young. When the height-normalized values (Table 3, Fig. 2Biii, iv, v) are considered, although there is a tendency for the dimensions in the M-L plane to be greater in young females than in young males, these differences are not significant, and in none of the parameters studied are there significant differences between the sexes in the young groups. In the middle groups, the values for the males are significantly greater than for the females in all parameters except the M-L and posterior CWs. In these latter two dimensions, although the mean values for males are greater, they are not significantly so. In the old groups, all anterior quadrant dimensions and the CWs in the M-L quadrants are significantly larger in males; none of the other parameters differ significantly between the sexes.

To summarize, when height is taken into account, the young groups are essentially indistinguishable. The greatest difference between the sexes is seen in the middle groups, spanning the menopausal period and its aftermath in females. At this stage, males have greater bone dimensions in all measured parameters. However, when CWs are considered, only the anterior shaft is significantly wider in males; the M-L and posterior are wider but not significantly so. The old groups resemble each other more than the middle groups, and again the greatest differences are seen in the anterior quadrant. Continued greater endocortical resorption in females also results in significantly smaller M-L CWs. The posterior shaft widths in the old groups, however, do not differ significantly.

DISCUSSION

This study shows that modeling changes follow a similar pattern in both sexes in that between young and old, the greatest radial dimensional alterations are seen in the M-L plane, with less in the anterior, and least in the posterior. As males age, the size and shape of the mid-femoral shaft alter, and the bones become larger and rounder; the greatest changes occur between the young and middle groups with apposition continuing in the elderly but more slowly. This is reflected in the significant increase in the mid-shaft index, indicating adaptation towards a greater bending rigidity in the M-L plane with age. Changes in the A-P plane are not as great and are more complex, in that the anterior and posterior cortices show different modeling patterns: there is more periosteal apposition on the anterior surface and very little on the posterior, favoring greater anterior loading with age. Endocortical resorption is greatest anteriorly and least posteriorly, as shown by the degree of decline in CW/RW ratios. However, absolute CWs are not significantly smaller in the elderly, and since bone has been redistributed to a more favorable location mechanically, bone loss in males appears to be compensated for.

If a height adjustment is made, young males and females have comparably sized mid-femoral shafts. Females, however, commence with more circular bones in young adulthood than males, and although the trend towards greater M-L bending rigidity continues with age, the mid-shaft index is not significantly different between young and old females. The result is that old males and old females resemble each other in the circularity of their mid-shafts. Although the RW changes in the M-L plane in females are not as great as in males, they still exceed the changes in the A-P plane. Again, as in the males, surface apposition on the anterior is greater than on the posterior. The most striking difference between males and females is in the timing of these modeling events: in females the greatest changes, both in terms of apposition and resorption, occur after the menopausal period, i.e., between the middle and old groups. Prior to this period there is very little change in bone dimensions, unlike in males, where trends towards an increase in height-normalized parameters are seen between the young and middle cohorts. The other major difference between the sexes is in the extent of resorption. In females there is a significant decline in CW/RW ratios in all quadrants, greatest in the anterior, as in males at this location. The absolute CWs also decrease, significantly so in the anterior, so that compensation for bone loss, at least in terms of bone quantity, is not as great in females. However, bone redistribution to a

mechanically more favorable location on the outer perimeter does occur, and may result in a not greatly weakened bone in the elderly female.

In summary, with age the femoral midshaft in both sexes becomes larger and more circular, with a slight shift towards the anterior. Apposition is least on the posterior perimeter and resorption greatest on the anterior endocortical surface, the latter being particularly evident in postmenopausal females. The greatest differences between the sexes are seen in the middle years, lessening again in the old.

The importance of this study of age and sex differences in regional femoral geometry lies in the fact that a large number of well-documented specimens of both sexes covering the entire adult life span were available. The age, supine length, weight, and in most cases, the cause of death (from autopsy reports) of each subject were known. Automatic image analysis techniques were utilized to ensure reproducibility. To our knowledge, this is the first time Fourier shape analysis has been used to assist in delineating the frequently problematic endocortical surface, thereby decreasing subjectivity and enhancing the consistency of the results. The data from this study have been derived from a modern, largely Anglo-Celtic population, and since the prevalence of conditions like osteoporosis is similar in Melbourne to that in urbanized populations of other Western countries (unpublished abstract, Seeman et al., 1993: The incidence of hip fractures of women and men in Australia), the findings should be widely applicable. Comparison of results from a large sample of a contemporary population with previously reported findings from archaeological populations may shed some light on the changes wrought in the skeleton by modern urban living.

Despite the relatively large sample available for study, group numbers were still insufficient to statistically substantiate some of the observed trends. A few other limitations affecting the study may be noted. For ease of calculation, the centroid of the periosteal outline was selected to define the radial width, and this is acknowledged as being arbitrary. Similarly, the choice of bisecting the linea aspera to define the A-P axis can also be considered arbitrary; this was necessitated by ignorance of the orientation of the specimens from the earlier collection. The same constraint applied to the medial and lateral sides; hence, the results presented in Table 1 compare these quadrants in the subsample where the precise orientation was known. Since no differences were observed, pooling the results from these quadrants was felt to be justified.

This was a cross-sectional study, so secular trends inevitably influenced the results. Height normalization was carried out in an attempt to minimize these cohort differences. In Australia, between 1901–1970, there was an average 4.6-cm (males) and 3.3-cm (females) increase in the height of young adults, i.e., a secular increase in height over this period of approximately 0.7 cm and 0.5 cm per decade for males and females, respectively (Meredith, 1976). The height decreases presented here between the young and old groups were much greater than can be accounted for by secular trends alone. With an approximately five-decade difference between the mean group ages, and assuming the above reported values of 0.7 cm (males) and 0.5 cm (females), this only explains a 3.5-cm and 2.5-cm decrease in males and females, respectively. The latter figures may be greater than in actuality, and they ignore the possibility that the secular increase in developed countries may have slackened or ceased in the second half of this century (Bakwin and McLaughlin, 1964). The remaining height difference of approximately 7 cm in males and 9 cm in females can be attributed to statural loss with age. Mazess et al. (1990) reported a 6.4-cm decrease between the third and ninth decades in a contemporary U.S. white male population. In another contemporary U.S. study, Galloway et al. (1990) reported a mean loss of 0.146 cm/year in females calculated from age 45, using reported maximum height. In our sample, excluding the assumed secular changes, there is a rate of statural loss of 0.19 cm/year for females and 0.14 cm/year for males over the five-decade span between young and old groups. The greater severity of height loss, particularly in older females, was observed also by Galloway et al. (1990). They suggested that there may be a secular

trend towards an increased rate of statural loss associated with the trend towards greater reductions in bone mineral density. Earlier studies reported smaller declines in statural loss (Hertzog et al., 1969; Himes and Mueller, 1977). Our observations support the suggestion of Galloway et al. (1990) that a secular trend towards an increase in statural loss with age may be occurring.

The secular trends discussed above help to explain some of the seeming inconsistencies observed in the results. For example, when the raw values are considered, in both males and females the A-P diameters show a tendency to be larger in the young than in the old. Similarly, in females the RWs tend to be smaller in the middle-aged group than in the young; yet, it is generally acknowledged that bones increase, rather than decrease, in size throughout life (Feik et al., 1996; Garn et al., 1967; Ruff and Hayes, 1982; Smith and Walker, 1964). The younger, taller cohorts have larger bones, and the amount of periosteal apposition that occurs with age in the above instances is insufficient to negate the secular increase. Even when the height-normalized values are considered, if little periosteal apposition occurs, the same tendency is seen, e.g., mean height-normalized A-P diameters in females are 16.5 mm (young) vs. 16.1 mm (middle). Thus also in this instance, the secular trends appear to outweigh the modeling changes.

Bone shape

The term "platycnemia," first coined by Busk in 1863, was used to describe a pronounced mediolateral flattening of the tibial shaft (Lovejoy et al., 1976). It has since been more broadly applied as a descriptor of bone "shape." In our study, young males showed a tendency towards greater platycnemia, i.e., less circularity, than young females. This implies that male mid-shafts are more adapted for A-P bending than those of females. A similar finding was reported by Ruff and Hayes (1983b) in bones from an archaeological population, the Pecos Pueblo. They attributed the sex difference to two factors: sexual dimorphism in pelvic structure, and different patterns of physical activity. In females the hip joint is placed further from the body center of gravity, increasing the M-L bending moment about the hip. This is thought to increase the M-L bending loading of the lower limb, leading to greater eurycnemia, i.e., increased circularity. The Pecos males purportedly engaged more in activities such as running and kicking than did the females. Such activities would favor platycnemia, for A-P bending stress increases dramatically during running (Carter, 1978; Lanyon et al., 1975).

Direct comparison between our study and that of Ruff and Hayes (1983a) is difficult, because they used I_{max}/I_{min} as a shape descriptor rather than the mid-shaft index. An I_{max}/I_{min} ratio close to 1.0 indicates near circularity of shape (Jungers and Minns, 1979). In the Pecos Pueblo sample, I_{max}/I_{min} at the femoral mid-shaft was 1.48 in males and 1.29 in females, i.e., a difference of 0.19. If we compare diameters in the A-P and M-L planes, we get ratios of 1.17 and 1.12 in young males and females, respectively. Modeling the bone sections as ellipses, the equivalent I_{max}/I_{min} ratios in our study are 1.37 for males and 1.25 in females, i.e., a difference of 0.12, slightly smaller than in the archaeological population. The equivalent values for I_{max}/I_{min} in a modern U.S. white population (Ruff, 1987) were 1.29 for males and 1.28 for females. These values show a much smaller difference between the sexes than in either the Pecos Pueblo sample or our modern collection. The values for females in both these modern populations are very similar. The much larger difference for males may be explained by the difference in mean ages of the two samples (42 years for the U.S. sample, 28 for the Australian). This is consistent with earlier results from the Australian sample that suggested that there was little or no change in bone geometry in premenopausal females (Feik et al., 1996).

A reduction in the platycnemic index of the tibia in modern samples has been noted (Lovejoy et al., 1976). The situation with regard to the femoral mid-shaft is less clear. After reviewing a number of studies, Ruff and Hayes (1983a) concluded that, although there was a suggestion of a somewhat more cylindrical mid-shaft in modern samples (an average 10% change), larger numbers were necessary to establish clear central tenden-

cies for this property in the femur because of its relative circularity.

Our study shows that with age, the femoral mid-shaft became more eurycnemic, approaching near-circularity in the old groups (mid-shaft index 0.95 in both sexes). This shape change could be explained in terms of changes in activity patterns with age. Habitual running tends to favor modeling to a more A-P area distribution, and walking to a relatively more M-L distributed cross-sectional shape (Lovejoy et al., 1976). Older people in Western societies walk rather than run and activity levels are lower (Sinclair and Dangerfield, 1998), and this may not differ greatly between the sexes. Among the young in Australia, male participation in sports has traditionally been greater than it has in females, and males engage in sports such as football, while females favor swimming (Australian Social Trends, 1999, Australian Bureau of Statistics). The magnitude of the effect of sexual dimorphism in pelvic structure on femoral mid-shaft shape is thrown into question by the identical values obtained for the mid-shaft index in old males and females, unless the pelvis also remodels with age.

The increased circularity of the femur with age was the result of greater apposition in the M-L plane than in the A-P plane, with a relatively greater change in males than females. Percentage RW increases in the A-P plane, however, did not differ significantly with age between the sexes. As mentioned above, a number of authors have documented continuing periosteal apposition with age, but not the specific site where this apposition occurs. Some have also reported that this compensation for bone lost endocortically is greater in males than females (Martin and Atkinson, 1977; Ruff and Hayes, 1988). Our study shows the magnitude and location of these modeling changes and how they differ between the sexes. Unlike the medial and lateral quadrants, which showed similar modeling changes, the anterior and posterior behaved differently. The posterior showed very little apposition, an approximate 3% nonsignificant change between young and old in both males and females, and a steady age-related decline in CW. The percentage RW increases in the anterior, however, were 2–3 times greater and significantly different between young and old, and the decline in CW was seen only in the old. The net result of these modeling changes is that an anterior cortical drift of the femoral mid-shaft occurs with age. Gait and posture changes may perhaps be invoked to explain this modeling. Craik (1989) reviewed the literature on changes in gait with age, and it is clear from her work that older people walk more slowly, with reduced step length and longer periods with both feet on the ground. The changes in femoral loading patterns resulting from this are unclear, but it has been suggested that alterations in functional strain distribution can initiate adaptive modeling (Biewener, 1991; Lanyon, 1992). Long-term change in exercise pattern has been shown to result in geometric adaptation of bones (Adami et al., 1999; Ashizawa et al., 1998; Suominen et al., 1998). Muscle strength decreases with age in the extremities and back by as much as 60% between 30–80 years (unpublished results, Faulkner JA and Brooks SV, Age-Related Immobility: The Roles of Weakness Fatigue, Injury, and Repair; see Buckwalter et al., 1993), and spinal curvature increases (Sinaki et al., 1998). The posture becomes stooping, the pelvic tilt decreases, altering the position of the center of gravity, and the head and thorax are thrust forward to compensate (Sinclair and Dangerfield, 1998). This presumably increases the anterior loading on the femur, resulting in the cortical drift documented in this study. Females, particularly those over 75 years (Galloway et al., 1990), show a greater statural loss with age than males, as mentioned above, and would thus be expected to show greater compensation. This in fact can be observed, for anterior apposition was three times greater in females than males between the middle and old groups (an increase of 3.1% in males and 9.3% in females).

As shown in Figure 2, the greatest difference between the sexes was seen between the middle groups. We reported previously (Feik et al., 1996) that in males, total subperiosteal area, polar moment of inertia, cortical area, and medullary area increase from the third or fourth decade at least into the 70s, whereas females show stability or even a tendency to a decline in these parameters until the sixth decade. In the present study, the RWs and CWs in all quadrants except the posterior showed similar pat-

terns of change. The posterior, as mentioned earlier, behaved differently, showing consistent age-related changes in both males and females. This may, perhaps, be attributed to the muscle insertions at the linea aspera influencing functional bone strains. Ferretti et al. (1998) reported that premenopausal women stored more mineral than age-matched men with comparable lean body mass, and suggested that the "surplus" mineral may be stored in the endocortical area, but they could not verify this because of the assessment method used (DEXA). Rutherford and Jones (1992) similarly found that in females, cortical bone in the mid-femur was maintained until the sixth decade.

Our study confirms these observations. It appears that in males, bone modeling shows a consistent age-related pattern, whereas females store bone endocortically during the reproductive period and lose this postmenopausally when it is no longer needed for pregnancy and lactation. The endocortical loss possibly triggers a compensatory mechanism, for periosteal apposition in the M-L and anterior quadrants increased greatly only at this stage (significant increase between middle and old groups). Estrogen deficiency elicits a large increase in erosion depth on the endocortical surface and increases bone turnover (33% increase in activation frequency) (Han et al., 1997). These hormonal changes probably account for the greater CW loss in postmenopausal females. Old individuals, like the young, are again more similar to each other, although females have larger medullary cavities despite having smaller bones (Fig. 2Bv). The difference may be due to continuing greater endocortical erosion depth, which may be maintained throughout life (Parfitt, 1990).

This study, using advanced image analysis techniques, reveals sex and age differences in regional modeling of the femoral mid-shaft. The mid-shaft, initially more A-P distributed in young males, becomes rounder with age, and the circularity of the shafts is identical in the old. This modern population shows greater eurycnemia and smaller sex differences than an archaeological population. Anterior cortical drift occurs in both sexes with age, more so in females, and may be the result of gait and posture changes that alter the loading on the femur. The findings from this study on a large, urbanized, contemporary Australian population may be widely applicable to other Western countries with similar lifestyles.

ACKNOWLEDGMENTS

The authors thank the mortuary staff at the Victorian Institute of Forensic Medicine, Melbourne, Australia, for collection of specimens, Dr. P.K. Bertelsen for advice and specimen preparation of a large part of the collection, and Sherie Blackwell for assistance with preparation of the manuscript and for technical support. We are also grateful to the National Institute of Forensic Science, which provided much of the computer equipment and software used for this study.

LITERATURE CITED

Adami S, Gatti D, Braga V, Bianchini D, Rossini M. 1999. Site-specific effects of strength training on bone structure and geometry of ultradistal radius in postmenopausal women. J Bone Miner Res 14:120–124.

Ashizawa N, Tajima O, Hayashi K, Shirasaki Y, Amagai H, Usuba M, Saitoh S, Tokuyama K, Suzuki M. 1998. Tomographic (pQCT) comparison of dominant and nondominant radius of 150 tennis players. Bone [Suppl] 23:470.

Bakwin H, McLaughlin S. 1964. Secular increase in height: is the end in sight? Lancet Dec 5:1195–1196.

Beck TJ, Ruff CB, Scott WW, Plato CC, Tobin JD, Quan CA. 1992. Sex differences in geometry of the femoral neck with aging: A structural analysis of bone mineral data. Calcif Tissue Int 50:24–29.

Beck TJ, Ruff CB, Bissessur K. 1993. Age-related changes in female femoral neck geometry: Implications for bone strength. Calcif Tissue Int [Suppl] 53: 41–46.

Beck TJ, Mourtada F, Ruff C, Looker A, Wahner H, Walters L. 1996. Derivation of geometric structural properties and stresses from the NHANES III DXA hip scan data. J Bone Miner Res 11:584 [abstract].

Bell KL, Loveridge N, Power J, Garrahan N, Stanton M, Lunt M, Meggitt BF, Reeve J. 1999. Structure of the femoral neck in hip fracture: cortical bone loss in the inferoanterior to superoposterior axis. J Bone Miner Res 14:111–119.

Biewener A. 1991. Musculoskeletal design in relation to body size. J Biomech [Suppl] 24:19–29.

Boereboom F, Raymakers J, de Groot R, Duursman S. 1992. Epidemiology of hip fractures in the Netherlands: women compared with men. Osteoporos Int 2:279–284.

Buckwalter JA, Woo SL, Goldberg VM, Hadley EC, Booth F, Oegema TR, Eyre DR. 1993. Soft-tissue aging and musculoskeletal function. J Bone Joint Surg [Am] 75:1533–1548.

Carter D. 1978. Anisotropic analysis of strain rosette information from cortical bone. J Biomech 11:199–202.

Craik R. 1989. Changes in locomotion in the aging adult. In: Woollacott M, Schumway-Cook A, editors.

Development of posture and gait across the lifespan. Columbia, SC: University of South Carolina Press. p 176–201.
De Laet CE, van Hout BA, Burger H, Hofman A, Pols HA. 1997. Bone density and risk of hip fracture in men and women: cross sectional analysis. Br Med J [Clin Res] 315:221–225.
Feik SA, Thomas CDL, Clement JG. 1996. Age trends in remodeling of the femoral midshaft differ between the sexes. J Orthop Res 14:590–597.
Feik SA, Thomas CDL, Clement JG. 1997. Age-related changes in cortical porosity of the midshaft of the human femur. J Anat 191:407–416.
Feldesman M, Fountain R. 1996. "Race" specificity and the femur/stature ratio. Am J Phys Anthropol 100: 207–224.
Ferretti JL, Capozza RF, Cointry GR, Garcia SL, Plotkin H, Alvarez Filgueira ML, Zanchetta JR. 1998. Gender-related differences in the relationship between densitometric values of whole-body bone mineral content and lean body mass in humans between 2 and 87 years of age. Bone 22:683–690.
Galloway A, Stini W, Fox S, Stein P. 1990. Stature loss among an older United States population and its relation to bone mineral status. Am J Phys Anthropol 83:467–476.
Garn SM, Rohmann CG, Wagner B, Ascoli W. 1967. Continuing bone growth throughout life: a general phenomenon. Am J Phys Anthropol 26:313–317.
Hamill P, Drizd T, Johnson C, Reed R, Roche A. 1977. NCHS growth curves for children birth—18 years. Vital Health Stat [11] 165:1–74.
Han ZH, Palnitkar S, Rao DS, Nelson D, Parfitt AM. 1997. Effects of ethnicity and age or menopause on the remodeling and turnover of iliac bone: implications for mechanisms of bone loss. J Bone Miner Res 12:498–508.
Hertzog K, Garn S, Hempy H. 1969. Partitioning the effects of secular trend and ageing on adult stature. Am J Phys Anthropol 31:111–115.
Himes J, Mueller W. 1977. Age-associated statural loss and socioeconomic status. J Am Geriatr Soc 25:171–174.
Judex S, Gross TS, Zernicke RF. 1997. Strain gradients correlate with sites of exercise-induced bone-forming surfaces in the adult skeleton. J Bone Miner Res 12:1737–1745.
Jungers W, Minns R. 1979. Computed tomography and biomechanical analysis of fossil long bones. Am J Phys Anthropol 50:285–290.
Lanyon LE. 1992. Control of bone architecture by functional load bearing. J Bone Miner Res 7:369–375.
Lanyon LE, Hampson W, Goodship J, Shah J. 1975. Bone deformation recorded in-vivo from strain gages attached to the human tibial shaft. Acta Orthop Scand 46:256–268.
Lestrel PE. 1997. Fourier descriptors and their applications in biology. Cambridge and New York: Cambridge University Press.
Lovejoy CO, Burnstein AH, Heiple KG. 1976. The biomechanical analysis of bone strength: a method and its application to platycnemia. Am J Phys Anthropol 44:489–506.
Luerkens D, Beddow J, Vetter F. 1982. Morphological Fourier descriptors. Powder Technol 31:209–215.
Martin RB, Atkinson PJ. 1977. Age and sex-related changes in the structure and strength of the human femoral shaft. J Biomech 10:223–231.
Martin RB, Pickett JC, Zinaich S. 1980. Studies of skeletal remodeling in aging men. Clin Orthop 149:268–282.
Mazess RB, Barden HS, Drinka PJ, Bauwens SF, Orwoll ES, Bell NH. 1990. Influence of age and body weight on spine and femur bone mineral density in US white men. J Bone Miner Res 5:645–652.
Melton LJ. 1993. Hip fractures; a worldwide problem today and tomorrow. Bone 14:1–8.
Meredith HV. 1976. Findings from Asia, Australia, Europe, and North America on secular change in mean height of children, youths, and young adults. Am J Phys Anthropol 44:315–326.
Mosley JR, March BM, Lynch J, Lanyon LE. 1997. Strain magnitude related changes in whole bone architecture in growing rats. Bone 20:191–198.
Parfitt A. 1990. The three organisational levels of bone remodeling—implications for the interpretation of biochemical markers and the mechanisms of bone loss. In: Christiansen C, Overgaard K, editors. Osteoporosis: proceedings of Third International Symposium. Copenhagen: Osteopress ApS. p 429–434.
Ruff C. 1987. Sexual dimorphism in human lower limb bone structure: relationship to subsistence strategy and sexual division of labour. J Hum Evol 16:391–416.
Ruff CB. 1984. Allometry between length and cross-sectional dimensions of the femur and tibia in *Homo sapiens sapiens*. Am J Phys Anthropol 65:347–58.
Ruff CB, Hayes WC. 1982. Subperiosteal expansion and cortical remodeling of the human femur and tibia with aging. Science 217:945–948.
Ruff CB, Hayes WC. 1983a. Cross-sectional geometry of Pecos Pueblo femora and tibiae—a biomechanical investigation: I. Method and general patterns of variation. Am J Phys Anthropol 60:359–381.
Ruff CB, Hayes WC. 1983b. Cross-sectional geometry of Pecos Pueblo femora and tibiae—a biomechanical investigation: II. Sex, age and side differences. Am J Phys Anthropol 60:383–400.
Ruff CB, Hayes WC. 1984. Bone-mineral content in the lower limb. Relationship to cross-sectional geometry. J Bone Joint Surg [Am] 66:1024–1031.
Ruff CB, Hayes WC. 1988. Sex differences in age-related remodeling of the femur and tibia.
J Orthop Res 6:886–896.
Ruff CB, Trinkaus E, Walker A, Larsen CS. 1993. Postcranial robusticity in *Homo*. I: temporal trends and mechanical interpretation. Am J Phys Anthropol 91: 21–53.
Rutherford O, Jones D. 1992. The relationship of muscle and bone loss and activity levels with age in women. Age Ageing 21:286–293.
Schwarcz H, Shane K. 1969. Measurement of particle shape by Fourier analysis. Sedimentology 13:213–231.
Sinaki M, Itoi E, Wahner H, Wollan P, Gelczer R, Collins D, Hodgson S. 1998. Effect of disproportionate loss of muscle strength on axial deformities with aging: 10-year follow up. Bone [Suppl] 23:624.
Sinclair D, Dangerfield P. 1998. Human growth after birth. Oxford, New York, and Tokyo: Oxford University Press.
Smith RW, Walker RR. 1964. Femoral expansion in aging women: implications for osteoporosis and fractures. Science 145:156–157.
Suominen H, Avikainen V, Cheng S, Ollikainen S, Puolakka J, Sipila S, Taaffe D, Timonen J, Toivanen J. 1998. Effects of high-impact physical exercise and estrogen replacement therapy on bone mineral density and cross-sectional geometry in postmenopausal women. Bone [Suppl] 23:383.
Woo S-Y, Kuel S, Amiel D, Gomez M, Hayes W, White F, Akeson W. 1981. The effect of prolonged physical training on the properties of long bone: a study of Wolff's law. J Bone Joint Surg [Am] 63:780–787.